

(19)

Europäisches Patentamt
European Patent Office
Office européen des brevets



(11)

EP 1 207 645 A1

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:
22.05.2002 Bulletin 2002/21

(51) Int Cl.7: H04L 1/00, H04B 7/06

(21) Application number: 01304722.0

(22) Date of filing: 29.05.2001

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU
MC NL PT SE TR
Designated Extension States:
AL LT LV MK RO SI

• Huang, Howard C.
New York, New York 10003 (US)
• Lozano, Angel
New York, New York 10006 (US)

(30) Priority: 16.11.2000 US 714084

(71) Applicant: LUCENT TECHNOLOGIES INC.
Murray Hill, New Jersey 07974-0636 (US)

(74) Representative:
Watts, Christopher Malcolm Kelway, Dr.
Lucent Technologies (UK) Ltd,
5 Mornington Road
Woodford Green Essex, IG8 0TU (GB)

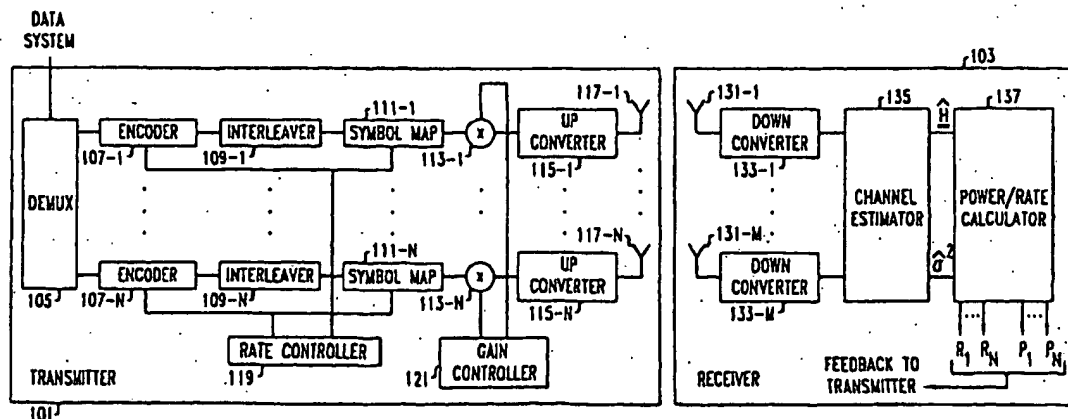
(72) Inventors:
• Chung, Seong-Taek
Mountain View, California 94041 (US)

(54) Feedback technique for wireless systems with multiple transmit and receive antennas

(57) In a wireless communication system using multiple antennas at the transmitter and multiple antennas at the receiver, a so called multiple-input multiple-output (MIMO) system, a substantial improvement in capacity over the case of no feedback can be achieved using considerably less bandwidth than is required to feed-back the channel estimate or channel statistics, by supplying as feedback for each data substream of an overall data stream an indicator of a rate and/or an indicator of a gain for transmission of that data substream. The in-

dicator of the rate and/or the indicator of the gain may be the rate and/or gain directly or an encoded representation of the rate and/or gain. Typically, the best performance is achieved if indicators of both the rate and the gain are fed back. If the invention is implemented for wireless systems, then typically for each data substream there is a separate, independent antenna. The rate and the gain are computed as a function of a channel estimate which is developed at the receiver. Advantageously, the transmitter may employ only one-dimensional data coding for each of the data substreams.

FIG. 1



EP 1 207 645 A1

Description**Technical Field**

[0001] This invention relates to the art of wireless communications, and more particularly, to wireless communication systems using multiple antennas at the transmitter and multiple antennas at the receiver, so called multiple-input multiple-output (MIMO) systems.

Background of the Invention

[0002] It is known in the art that multiple-input multiple-output (MIMO) systems can achieve dramatically improved capacity as compared to single antenna, i.e., single antenna to single antenna or multiple antenna to single antenna, systems. It is also known in the art that if a channel estimate or channel statistics based on the channel estimate are fed back to the transmitter, then the throughput of the channel can be improved with respect to an identically configured system but without feedback. However, because in MIMO systems the overall channel is actually made up of multiple channels, with one channel for each transmit and receive pairing, such feedback requires considerable bandwidth, and it is undesirable to dedicate so much bandwidth to feedback.

Summary of the Invention

[0003] In a MIMO system, a substantial improvement over the case of no feedback can be achieved using considerably less bandwidth than is required to feedback the channel estimate or channel statistics, in accordance with the principles of the invention, by supplying as feedback for each data substream of an overall data stream an indicator of a rate and/or an indicator of a gain for transmission of that data substream. The indicator of the rate and/or the indicator of the gain may be the rate and/or gain directly or an encoded representation of the rate and/or gain. Typically, the best performance is achieved if indicators of both the rate and the gain are fed back. If the invention is implemented for wireless systems, then typically for each data substream there is a separate, independent antenna. The rate and the gain are computed as a function of a channel estimate which is developed at the receiver. Advantageously, the transmitter may employ only one-dimensional data coding for each of the data substreams.

Brief Description of the Drawing

[0004] In the drawing:

FIG. 1 shows an exemplary multiple-input multiple-output (MIMO) system arranged in accordance with the principles of the invention so as to achieve dramatically improved capacity as compared to single

antenna systems; and

FIG. 2 shows an exemplary process for determining rates and powers for a system with N transmit substreams and M receive branches, in accordance with an aspect of the invention.

Detailed Description

[0005] The following merely illustrates the principles of the invention. It will thus be appreciated that those skilled in the art will be able to devise various arrangements which, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples and conditional language recited herein are principally intended expressly to be only for pedagogical purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor(s) to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

[0006] Thus, for example, it will be appreciated by those skilled in the art that the block diagrams herein represent conceptual views of illustrative circuitry embodying the principles of the invention. Similarly, it will be appreciated that any flow charts, flow diagrams, state transition diagrams, pseudocode, and the like represent various processes which may be substantially represented in computer readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

[0007] The functions of the various elements shown in the FIGs., including functional blocks labeled as "processors" may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a single dedicated processor, by a single shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term "processor" or "controller" should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, read-only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage. Other hardware, conventional and/or custom, may also be included. Similarly, any switches shown in the FIGs. are conceptual only. Their function may be carried out through the operation of program logic, through dedicat-

ed logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the implementor as more specifically understood from the context.

[0008] In the claims hereof any element expressed as a means for performing a specified function is intended to encompass any way of performing that function including, for example, a) a combination of circuit elements which performs that function or b) software in any form, including, therefore, firmware, microcode or the like, combined with appropriate circuitry for executing that software to perform the function. The invention as defined by such claims resides in the fact that the functionalities provided by the various recited means are combined and brought together in the manner which the claims call for. Applicant thus regards any means which can provide those functionalities as equivalent as those shown herein.

[0009] FIG. 1 shows an exemplary multiple-input multiple-output (MIMO) system arranged in accordance with the principles of the invention so as to achieve dramatically improved capacity as compared to single antenna systems. In particular, FIG. 1 shows transmitter 101 and receiver 103. Transmitter 101 includes a) demultiplexer (demux) 105; b) encoders 107, including encoders 107-1 through 107-N; c) interleavers 109, including interleavers 109-1 through 109-N; d) symbol mappers 111, including symbol mappers 111-1 through 111-N; e) gain multipliers 113, including gain multipliers 113-1 through 113-N; f) optional upconverters 115, including optional upconverters 115-1 through 115-N; g) optional transmit antennas 117, including optional transmit antennas 117-1 through 117-N; h) rate controller 119; and i) gain controller 121. Receiver 103 includes a) optional receive antennas 131, including optional receive antennas 131-1 through 131-M; b) optional downconverters 133, including optional downconverters 133-1 through 133-M; c) channel estimator 135; and d) power/rate calculator 137.

[0010] Demultiplexer 105 receives as an input an overall data stream, which is the data to be transmitted, and divides it into N data substreams, each to be processed along an independent transmit path and then transmitted.

[0011] Each of encoders 107 applies channel coding to the respective data substream it receives so as to increase the redundancy of the data substream. This facilitates error recovery at the receiver should errors occur. In accordance with an aspect of the invention, the type of channel coding used is a function of the rate, or an indicator thereof, that is fed back from the receiver. This function may be implemented using a lookup table given an indicator of the rate that is fed back, and is typically implemented by rate controller 119. Those of ordinary skill in the art will readily appreciate how to arrange such a function given the particular details of the system being implemented; e.g., the channel statistics, the number of substreams employed, and the like. The

type of channel coding employed determines the particular amount of redundancy in the encoded data substream, and it is noted that the amount of redundancy is known as the code rate. Each of encoders 107 may use a channel coding that is independent of the channel coding used by any other of encoders 107, and each may receive an independently specified rate.

[0012] Interleavers 109 are conventional in nature and each rearranges the bits of the encoded data substream it receives to provide protection against channel fades.

[0013] Each of symbol mappers 111 maps the bits of the interleaved encoded channel substream that it receives to a point in a constellation. In accordance with an aspect of the invention, the particular constellation employed is selected as a function of the rate, or an indicator thereof, that is fed back from the receiver. This function may be implemented using a lookup table given an indicator of the rate that is fed back, and is typically implemented by rate controller 119. Those of ordinary skill in the art will readily appreciate how to arrange such a function given the particular details of the system being implemented, e.g., the channel statistics, the number of substreams employed, and the like. Typically, the lower the rate of data transmission the lower the number of symbols in the constellation for transmitting data at that rate.

[0014] In accordance with an aspect of the invention, each of gain multipliers 113 applies to the mapped data substream that it receives the gain that was indicated in the feedback from the receiver. In an exemplary embodiment of the invention, the better the particular channel that corresponds to one of gain multipliers 113 the greater the gain that is applied, e.g., in accordance with the principles of waterfilling.

[0015] Each of optional upconverters 115 performs conventional upconverting functionality. In the case of a radio-based system each of upconverters 115 generates a radio frequency signal by modulating a carrier waveform using the gain regulated mapped data substream it receives as an input. Each resulting modulated signal may be supplied to the respective one of optional transmit antennas 117 that may be coupled to each of upconverters 115.

[0016] Rate controller 119 receives the rates, or indicators thereof, via feedback from receiver 103 and derives from the received information the code rate and the constellation size for each substream. Each code rate, or an indicator thereof, is then supplied to the appropriate encoder and the constellation to employ, or an indicator thereof, is supplied to each symbol mapper, in accordance with an aspect of the invention. Thus, rate controller 119 may implement a mapping function to determine the code rate and constellation from the information fed back from receiver 103.

[0017] Gain controller 121 receives the gains, or indicators thereof, via feedback from receiver 103 and derives from the received information the gain to be used

for each substream by the associated one of gain multipliers 113. Note that there is a direct relationship between power and gain. More specifically, power is converted to gain by taking the square root of the power. Thus, power may be an indicator for gain, and vice-versa. If power information is received via feedback, it may easily be converted into the appropriate gain.

[0018] Note that the functionality of rate controller 119 may be incorporated into encoders 107 and symbol mappers 111. Similarly, the functionality of gain controller 121 may be incorporated into gain multipliers 113.

[0019] Each of optional receive antennas 131 receives a signal from each of optional transmit antennas 117. The signals received at each antenna are converted to baseband by the one of optional downconverters 133 to which it is coupled. The resulting baseband signals are fed into channel estimator 135.

[0020] Channel estimator 135 develops an estimate of the channels for each transmit and receive pair. Thus, for N transmit antennas and M receive antennas there are $N \times M$ channels. The estimates for each of the channels are collectively arranged into an $N \times M$ matrix of the overall channel estimate \hat{H} . Additionally, channel estimator 135 develops an estimate of the noise power in the channel, $\hat{\sigma}^2$.

[0021] \hat{H} and $\hat{\sigma}^2$ are supplied to power/rate calculator 137 which, in accordance with the principles of the invention, calculates the rates R and powers P —which, as noted above, correspond directly to gains and are used by transmitter 101 in the form of gains—or indicators thereof, that transmitter 101 should use for each data substream produced by demultiplexer 105. The rates and powers are supplied to transmitter 101 using a feedback channel.

[0022] The processes by which rates and powers are assigned by power/rate calculator 137 is up to the implementor. Those of ordinary skill in the art will be able to develop their own processes given the discussion and examples hereinbelow. In particular, the goal of the process is to assign rates and powers to maximize the total channel capacity. Toward this end, typically, those channels that are of a better quality will be assigned higher rates and greater power.

[0023] Note that receiver 103 does not show a decoder and a deinterleaver. This is because, although a decoder and a deinterleaver are necessary for a complete receiver—to reverse the complementary functions performed in the transmitter prior to supplying data as an output of receiver 103—they are not required for the data streams that are supplied to channel estimator 135, and so that are not shown for the sake of clarity of exposition.

[0024] FIG. 2 shows an exemplary process for determining rates and powers for a system with N transmit substreams and M receive branches, in accordance with an aspect of the invention. In one embodiment of the invention, the process of FIG. 2 may be constantly running. However, the values determined by the proc-

ess are only fed back when there is a significant deviation from the values that were previously fed back. In another embodiment of the invention, the process may begin to run only when channel estimator 135 (FIG. 1) determines that the channel has changed by an amount sufficient to warrant the running of the process. For example, when the norm of the difference of \hat{H} at the last time rates and powers were determined and \hat{H} at the current time is greater than a prescribed threshold. The process of FIG. 2 is performed by power/rate calculator 137 (FIG. 1).

[0025] The process is entered in step 200 (FIG. 2) when it is determined that the rates and powers are to be computed. In step 201 several variables are initialized. In particular, a counter, n , is initialized to the value of N and the value of variable $P_{\text{remaining}}$ is initialized to P_T , which is the total transmit power available in the system in which the process of FIG. 2 is being employed. Next, in step 203, an initial power allocation of $P_{\text{remaining}}$, denoted as P_n , is assigned to the n^{th} substream. The value of $R_n = \log_2(1 + P_n h_n^H (H_{n+1:N} P_{n+1:N} H_{n+1:N}^H + I)^{-1} h_n)$ ($n = 1, \dots, N$) is calculated in step 205, where

$$h_n = [h_{n,1} \dots h_{n,M}]^T$$

is the complex M -dimensional vector for the n^{th} transmit substream;

$h_{m,n}$ is the complex channel coefficient from the n^{th} transmit substream to the m^{th} receive branch, with $m = 1 \dots M$;

superscript T indicates the matrix transpose operation;

$H_{n+1:N} = [h_{n+1,1} \dots h_{N,1} \dots h_{n+1,M} \dots h_{N,M}]$ is an M -by- $(N-n)$ matrix;

$P_{n+1:N} = \text{diag}(P_{n+1}, \dots, P_N)$ is the diagonal $(N-m)$ matrix of assigned powers;

superscript H indicates the Hermitian transpose operation;

superscript -1 denotes the matrix inverse; and

I is the identity matrix of size $M \times M$.

[0026] In step 207, the value of R_n is quantized to the nearest step size, e.g., the nearest integer, the nearest integer which is a multiple of a selected integer, or the nearest multiple of a selected value, or the like. The quantized value of R_n is denoted as \bar{R}_n .

[0027] The power of the current substream n is recalculated in step 209. This may be performed by calculating

$$\bar{P}_n = \frac{2^{\bar{R}_n} - 1}{h_n^H (H_{n+1:N} P_{n+1:N} H_{n+1:N}^H + I)^{-1} h_n}$$

where \bar{P}_n indicates a recalculated power. Conditional branch point 211 tests to determine if $P_{\text{remaining}} - \bar{P}_n > 0$.

This test determines if the amount of power remaining is greater than the amount of power that is allocated for substream n , i.e., the power allocation can actually be performed since there is enough power remaining to support it. If the test result in step 211 is YES, indicating that the power allocation can actually be performed, control passes to step 213, in which the counter n is decremented and $P_{\text{remaining}}$ is set to $P_{\text{remaining}} - \bar{P}_n$.

[0028] Conditional branch point 215 tests to determine if $n=0$, i.e., have all the substreams been processed. If the test result in step 215 is NO, control passes back to step 203 and the process continues as described above. If the test result in step 215 is YES, control passes to step 217 and the process exits.

[0029] If the test result in step 211 is NO, indicating that the power allocation cannot actually be performed, control passes to step 219 in which \bar{R}_n is set equal to value of R_n quantized down to the nearest step size value that is less than R_n , e.g., the nearest integer lower than R_n , the nearest integer which is a multiple of a selected integer and is lower than R_n , or the nearest multiple of a selected value and is lower than R_n , or the like. This will result in a lower value of \bar{P}_n . Control then passes back to step 209 and the process continues as described above.

[0030] Once the process of FIG. 2 has completed the rates and powers that were generated may be supplied via a feedback path for use in a transmitter. Alternatively, the rates and powers may be encoded so that they are represented by indicators which may be interpreted by the transmitter to determine the appropriate rates and powers—and hence gains. Also, as noted above, the powers may be converted into gains in the receiver, and the gain information directly, or encoded representations thereof, may be supplied via the feedback path for use in the transmitter. Furthermore, in accordance with an aspect of the invention, only information about the rates, or only information about the powers—and hence gains—may be fed back to achieve an improvement over the prior art, although feeding back both results in better performance.

Claims

1. A transmitter of a multiple-input multiple-output (MIMO) system for transmitting a plurality of data substreams derived from a data stream, comprising:

means for receiving as feedback an indicator of a rate and a power for each data substream; and

means for applying to each respective data substream a rate control and a power control corresponding to said indicator of a rate and a power received for said data substream.

2. The invention as defined in claim 1 wherein said in-

dicator of a rate and a power includes an independent denotation of said rate and an independent denotation of said power.

3. The invention as defined in claim 1 wherein said indicator of a rate and a power is said rate and said power.
4. The invention as defined in claim 1 wherein said indicator of a rate and a power is a value which is directly a function of said rate and said power indicated by said indicator.
5. The invention as defined in claim 1 wherein each rate and power are determined by a receiver as a function of channel estimates.
6. A receiver of a multiple-input multiple-output (MIMO) system for receiving a plurality of data substreams derived from a data stream, comprising:

means for estimating channel characteristics; and

means for deriving an indicator of a rate and an indicator of a power for each data substream as a function of estimated channel characteristics developed by said means for estimating; and

means for transmitting said indicator of said rate and said indicator of said power as feedback to a transmitter.

7. A transmitter of a multiple-input multiple-output (MIMO) system for transmitting a plurality of data substreams derived from an overall data stream, comprising:

a plurality of encoders, one encoder for each of said data substreams, each of said encoders being responsive to rate information received as feedback from a receiver of said substreams transmitted by said transmitter; and a plurality of symbol mappers, each of said symbol mappers coupled to receive a respective encoded version of one of said data substreams, and each of said symbol mappers also being responsive to said rate information.

8. The invention as defined in claim 7 further comprising a plurality of gain multipliers responsive to power information received as part of said feedback from said receiver.
9. The invention as defined in claim 7 further comprising a plurality of interleavers, each respective one of said interleavers being coupled between a respective one of said encoders and a respective one of said symbol mappers.

10. The invention as defined in claim 7 wherein each of said symbol mappers is associated with a respective one of said encoders for a respective one of said data substreams.
11. The invention as defined in claim 7 wherein each of said symbol mappers is associated with a respective one of said encoders along a transmit path for a respective one of said data substreams, and for each transmit path its associated encoder and symbol mapper receive the same rate from said rate information.
12. The invention as defined in claim 7 further comprising a rate controller for supplying to each of said symbol mappers and said encoders a rate to be used in response to said rate information.
13. The invention as defined in claim 7 further comprising a rate controller for supplying to each of said symbol mappers and said encoders a rate to be used in response to said rate information as a function of said rate information which is received in an encoded format.
14. The invention as defined in claim 7 further comprising a rate controller for supplying to each of said symbol mappers and said encoders a rate to be used in response to said rate information.
15. A transmitter of a multiple-input multiple-output (MIMO) system for transmitting a plurality of data substreams derived from an overall data stream, comprising:
 - a plurality of gain appliers, one gain applier for each of said data substreams, each of said gain appliers being responsive to power information received as feedback from a receiver of said substreams transmitted by said transmitter.
16. The invention as defined in claim 15 wherein said gain applier is a multiplier.
17. The invention as defined in claim 15 further comprising a gain controller for supplying to each of said gain appliers a power to be used in response to said power information.
18. The invention as defined in claim 15 further comprising a gain controller for supplying to each of said gain appliers a power to be used as a function said power information which is received in an encoded format.
19. A receiver of a multiple-input multiple-output (MIMO) system for receiving a plurality of data substreams derived from an overall data stream, comprising:
 - a channel estimator for developing (i) an overall channel estimate from said received plurality of data substreams and (ii) an estimate of noise power in said overall channel; and
 - a power calculator for calculating powers, one for each respective one of said substreams, to be used by a transmitter of said substreams.
20. A receiver of a multiple-input multiple-output (MIMO) system for receiving a plurality of data substreams derived from an overall data stream, comprising:
 - a channel estimator for developing (i) an overall channel estimate from said received plurality of data substreams and (ii) an estimate of noise power in said overall channel; and
 - a rate calculator for calculating rates, one for each respective one of said substreams, to be used by a transmitter of said substreams.
21. A method for use in processing for transmission in a multiple-input multiple-output (MIMO) system a plurality of data substreams derived from an overall data stream, the method comprising the steps of:
 - encoding each of said data substreams as a function of each indicator of a respective rate received as feedback from a receiver of said MIMO system for each of said data substreams to produce encoded data substreams; and
 - mapping each of said encoded data substreams after they are each respectively interleaved, said mapping for each of said encoded interleaved data stream being performed using a constellation selected as a function of each of said indicators of said respective rate received as feedback from a receiver of said MIMO system for each of said data substreams to produce encoded interleaved mapped data substreams.
22. The invention as defined in claim 21 further comprising the step of controlling the power of each of said encoded interleaved mapped data substreams as a function of respective indicators received as feedback from said receiver of said MIMO system for power control of each of said encoded interleaved mapped data substreams.
23. The invention as defined in claim 22 wherein there are N transmit paths, one for each data substream and M receive paths, so that there are NxM channels, said indicators and said rates are developed in said receiver by the steps of:

developing overall channel estimate \hat{H} , which is an NxM matrix;
 determine a noise power in the channel, $\hat{\sigma}^2$;
 initializing counter n to the value of N;
 initializing variable $P_{\text{remaining}}$ to the total transmit power available in the system P_T ;
 assigning an initial power allocation of the n^{th} substream P_n to a value of $P_{\text{remaining}}/n$;
 computing $R_n = \log_2(1 + P_n h_n^H (H_{n+1:N} P_{n+1:N} H_{n+1:N}^H + I)^{-1} h_n)$ ($n = 1, \dots, N$)
 where

R_n is a rate to use for the for the n^{th} transmit substream;

$$h_n = [h_{1,n} \dots h_{M,n}]^T$$

is the complex M-dimensional vector for the n^{th} transmit substream;
 $h_{m,n}$ is the complex channel coefficient from the n^{th} transmit substream to the m^{th} receive branch, with $m = 1 \dots M$;
 superscript T indicates the matrix transpose operation;
 $H_{n+1:N} = [h_{n+1,1} \dots h_{M,n+1}]$ is an M-by-(N-n) matrix;
 $P_{n+1:N} = \text{diag}(P_{n+1} \dots P_N)$ is the diagonal (N-m) matrix of assigned powers;
 superscript H indicates the Hermitian transpose operation;
 superscript -1 denotes the matrix inverse;
 and
 I is the identity matrix of size M x M;

quantizing R_n to the nearest step size to develop \bar{R}_n ; and
 recalculating the power of current substream n by calculating

$$\bar{P}_n = \frac{2^{\bar{R}_n} - 1}{h_n^H (H_{n+1:N} P_{n+1:N} H_{n+1:N}^H + I)^{-1} h_n}$$

where \bar{P}_n indicates a recalculated power.

24. The invention as defined in claim 22 further comprising the following steps when $P_{\text{remaining}} - \bar{P}_n > 0$

decrementing n;
 setting $P_{\text{remaining}}$ to $P_{\text{remaining}} - \bar{P}_n$; and
 when n is not equal to zero, repeating said assigning, computing, quantizing, and recalculating steps.

25. The invention as defined in claim 22 further comprising the following steps when $P_{\text{remaining}} - \bar{P}_n \leq 0$

setting \bar{R}_n equal to value of R_n quantized down to the nearest step size value that is less than R_n ; and
 repeating said recalculating step.

26. A method for use in a receiver of a multiple-input multiple-output (MIMO) system, in which there are N transmit paths, one for each data substream to be transmitted and M receive paths, so that there are NxM channels in an overall channel, the method comprising the steps of:

developing overall channel estimate \hat{H} , which is an NxM matrix;
 determine a noise power in the channel, $\hat{\sigma}^2$;
 initializing counter n to the value of N;
 initializing variable $P_{\text{remaining}}$ to the total transmit power available in the system P_T ;
 assigning an initial power allocation of the n^{th} substream P_n to a value of $P_{\text{remaining}}/n$;
 computing $R_n = \log_2(1 + P_n h_n^H (H_{n+1:N} P_{n+1:N} H_{n+1:N}^H + I)^{-1} h_n)$ ($n = 1, \dots, N$)
 where

R_n is a rate to use for the for the n^{th} transmit substream;

$h_n = [h_{1,n} \dots h_{M,n}]^T$ is the complex M-dimensional vector for the n^{th} transmit substream;

$h_{m,n}$ is the complex channel coefficient from the n^{th} transmit substream to the m^{th} receive branch, with $m = 1 \dots M$;
 superscript T indicates the matrix transpose operation;

$H_{n+1:N} = [h_{n+1,1} \dots h_{M,n+1}]$ is an M-by-(N-n) matrix;
 $P_{n+1:N} = \text{diag}(P_{n+1} \dots P_N)$ is the diagonal (N-m) matrix of assigned powers;

superscript H indicates the Hermitian transpose operation;
 superscript -1 denotes the matrix inverse;
 and

I is the identity matrix of size M x M;

quantizing R_n to the nearest step size to develop \bar{R}_n ; and
 recalculating the power of current substream n by calculating

$$\bar{P}_n = \frac{2^{\bar{R}_n} - 1}{h_n^H (H_{n+1:N} P_{n+1:N} H_{n+1:N}^H + I)^{-1} h_n}$$

where \bar{P}_n indicates a recalculated power.

27. The invention as defined in claim 26 further comprising the following steps when $P_{\text{remaining}} - \bar{P}_n > 0$

decrementing n ;
setting $P_{\text{remaining}}$ to $P_{\text{remaining}} - \bar{P}_n$; and
when n is not equal to zero, repeating said as-
signing, computing, quantizing, and recalculat-
ing steps.

5

28. The invention as defined in claim 26 further com-
prising the following steps when $P_{\text{remaining}} - \bar{P}_n \leq 0$

setting \bar{R}_n equal to value of R_n quantized down
to the nearest step size value that is less than
 R_n ; and
repeating said recalculating step.

10

15

20

25

30

35

40

45

50

55

8

FIG. 1

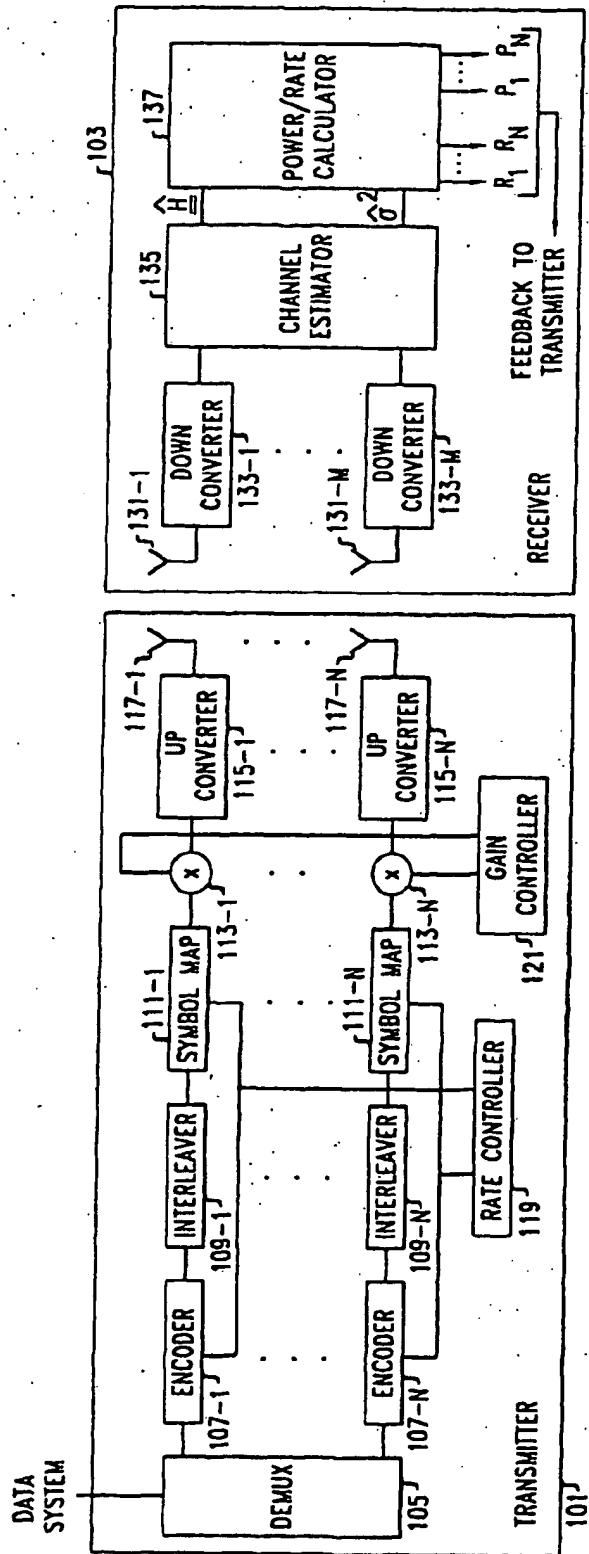


FIG. 2

